15 Terrestrial Laser Scanning Specifications

15   Terrestrial Laser Scanning

Laser scanning or Light Detection And Ranging (LiDAR) systems use lasers to make measurements from a tripod or other stationary mount, a mobile surface vehicle, or an aircraft. The term LiDAR is sometimes used interchangeably with laser scanning, but is more often associated with the airborne method, performed from an airplane, helicopter or other aircraft. Terrestrial Laser Scanning (TLS) as discussed in this Chapter does not pertain to airborne LiDAR or Airborne Laser Scanning (ALS), which will be addressed in a future revision of the *Caltrans Surveys Manual (CSM)*, Chapter 13, Photogrammetry.

Survey specifications describe the methods and procedures needed to attain a desired survey accuracy standard. For complete accuracy standards, refer to *CSM* Chapter 5, "Classifications of Accuracy and Standards." Caltrans survey specifications shall be used for all Caltrans-involved transportation improvement projects, including special-funded projects.

Caltrans survey specifications for general order TLS surveys typically performed by or for the Department are based on research projects and field experience. As equipment and procedures improve, new specifications will be developed and existing specifications will be changed. In the interim, District Surveys Managers may approve use of methods and procedures not addressed in the *CSM*.

15.1 Stationary Terrestrial Laser Scanning

Stationary Terrestrial Laser Scanning (STLS) refers to laser scanning applications that are performed from a static vantage point on the surface of the earth. STLS instruments for civil engineering projects typically use "time-of-flight," "phase based," (See Figure 15-1) or "waveform processing" technology to measure distances (See Figure 15-2). The basic concept is similar to that used in total station instruments; using the speed of light to determine distance. However, there are significant differences in laser light wavelength, amount and speed of point data collected, field procedures, data processing, error sources, etc. Laser scanning systems collect a massive amount of raw data called a "point cloud."

Time-of-flight (also known as "pulse based") scanners are the most common type of laser scanner for civil engineering projects because of their longer effective maximum range (typically 125-1000m) and data collection rates of 50,000 points per second, or more. A time-of-flight laser scanner combines a pulsed laser emitting the beam, a mirror deflecting the beam towards the scanned area, and an optical receiver subsystem, which detects the laser pulse reflected from the object. Since the speed of light is known, the travel time of the laser pulse can be converted to a precise range measurement.

A phase based laser scanner modulates the emitted laser light into multiple phases and compares the phase shifts of the returned laser energy. The scanner uses phase-shift algorithms to determine the distance based on the unique properties of each individual phase. Phase based laser scanners have a shorter maximum effective range (typically 25-75m) than time-of-flight scanners, but have much higher data collection rates than time-of-flight scanners.

Waveform processing, or echo digitization laser scanners use pulsed time-of-flight technology and internal real-time waveform processing capabilities to identify multiple returns or reflections of the same signal pulse resulting in multiple object detection (See Figure 15-2). Waveform processing laser scanners have a maximum effective range similar to that of time-of-flight scanners. With a pulse rate of 300,000 pulses per second, and an echo detection capability of 15 returns per pulse, actual data collection rates can exceed 1.5 million points per second. Waveform processing scanners have trouble discriminating between returns of the same laser pulse from objects that are closely spaced. The discrimination limit (Shown as "d" in Figure 15-2) is a function of laser emitter and receiver operating parameters. Returns from objects closer together than the laser scanner's multiple object discrimination limit will create false points in the data. See:
http://cipa.icomos.org/text%20files/KYOTO/48.pdf

The raw data product of a laser scan survey is a point cloud. When the scanning control points are georeferenced to a known coordinate system, the entire point cloud can be oriented to the same coordinate system. All points within the point cloud have X, Y, and Z coordinate and laser return Intensity values (XYZI format). The points may be in an XYZIRGB (X, Y, Z coordinate, return Intensity, and Red, Green, Blue color values) format if image overlay data is available. The positional error of any point in a point cloud is equal to the accumulation of the errors of the scanning control and errors in the individual point measurements.

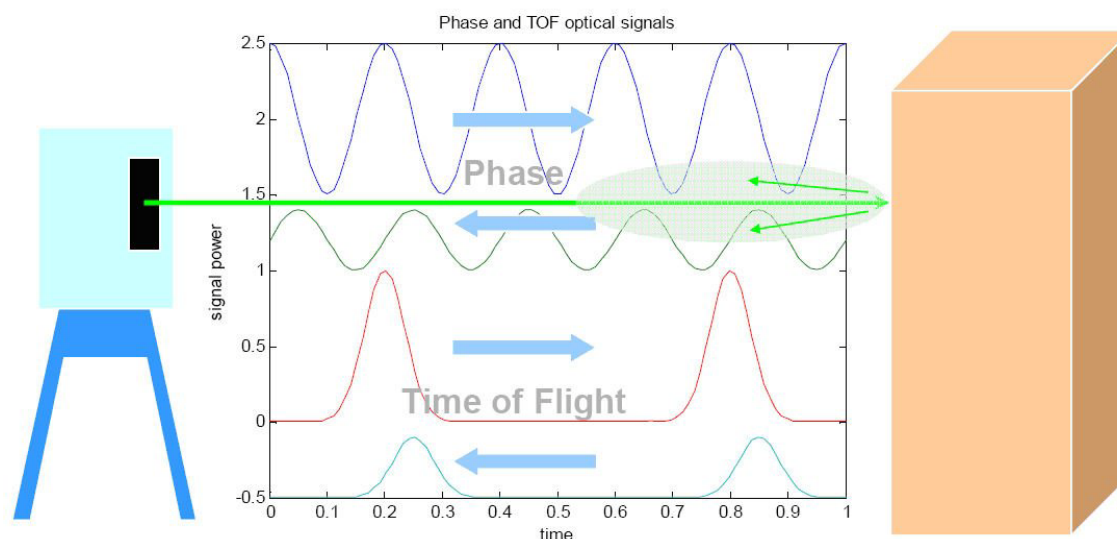**Figure 15-1 Working principle of phase based and time-of-flight laser scanners**

Image courtesy of the UC Davis AHMCT Research Center: http://www.ahmct.ucdavis.edu

Just as with reflectorless total stations, laser scan measurements that are perpendicular to a surface will produce better accuracies than those with a large angle of incidence to the surface. The larger the angle, the more the beam can elongate, producing errors in the distance returned. Waveform system elongation errors have been documented and can be corrected. (See: "Improving quality of laser scanning data acquisition through calibrated amplitude and pulse deviation measurement" by Martin Pfennigbauer and Andreas Ullrich, Proc. SPIE 7684, 76841F (2010), DOI:10.1117/12.849641 www.SPIEDigitalLibrary.org)

Data points will also become more widely spaced as distance from the scanner increases and less laser energy is returned. At a certain distance the error will exceed standards and beyond that no data will be returned. Atmospheric factors such as heat radiation, rain, dust, and fog will also limit scanner effective range.

While terrestrial laser scanning may result in less field time to complete complex projects, data extraction and production of usable Computer Aided Design and Drafting (CADD)/ Digital Terrain Model (DTM) format products currently takes considerable office time. The field to office processing time ratio increases with point density, complexity of the object(s) being scanned, and deliverable detail. Resources for data extraction (computers, programs, and trained personnel) can be a limitation.

For in-depth discussions of stationary LiDAR, see the AHMCT Research Center reports "Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects" http://www.ahmct.ucdavis.edu/images/AHMCT_LiDARFinalReport.pdf, "Accelerated Project Delivery: Case Studies and Field Use of 3D Terrestrial Laser Scanning in Caltrans Projects: Phase I - Training and Materials" http://www.ahmct.ucdavis.edu/images/UCD_ARR_08_06_30_06.pdf. and: http://hds.leica-geosystems.com/hds/en/Investigating_Acurracy_Mintz_White_Paper.pdf

Figure 15-2 Working principle of waveform processing laser scanners
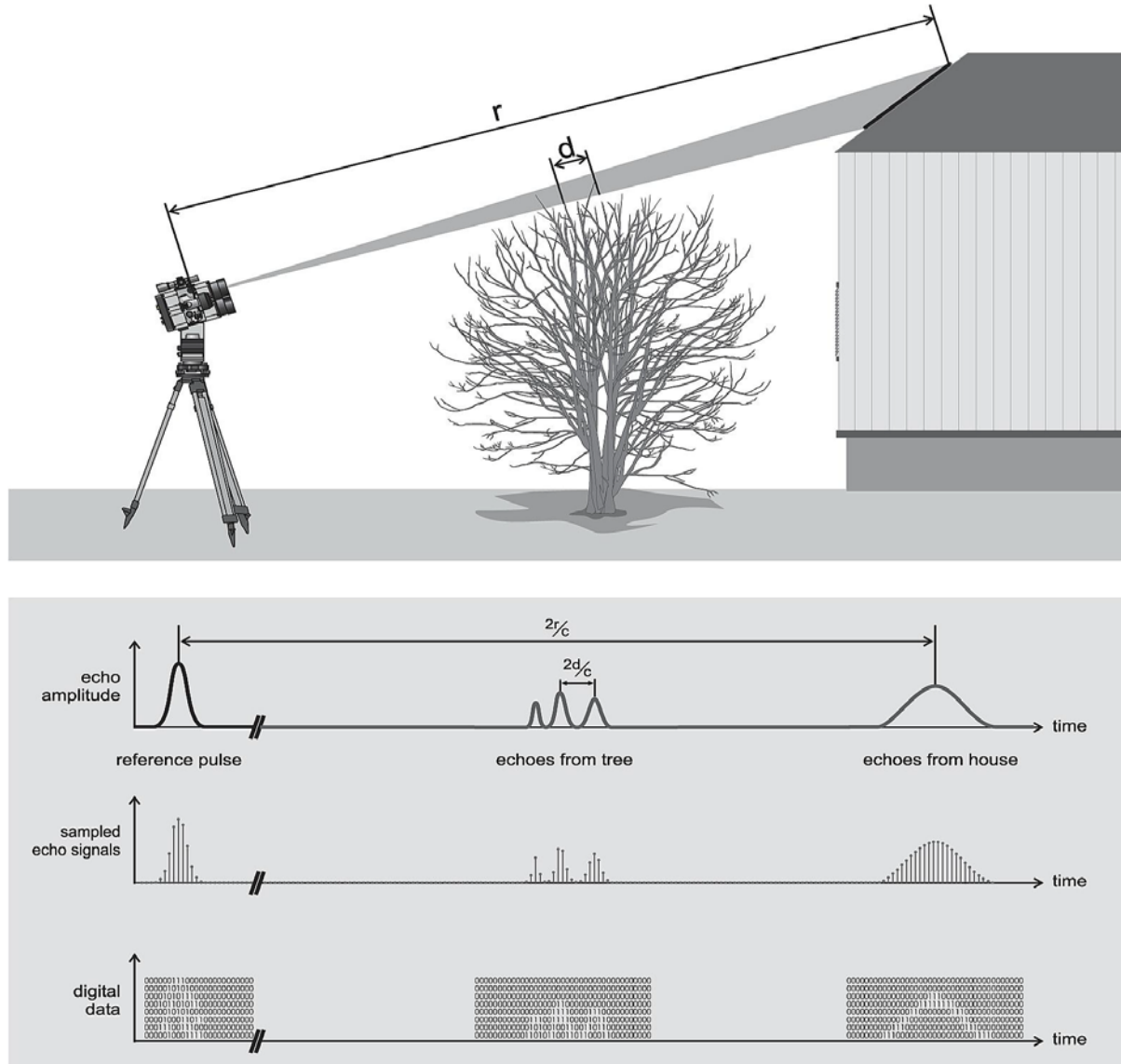
Image originally published in "Three-dimensional laser scanners with echo digitization" Pfennigbauer, M. and Ullrich, A. in *Laser Radar Technology and Applications XIII*. Edited by Turner, Monte D.; Kamerman, Gary W. in the Proceedings of The International Society for Optical Engineering (SPIE), Vol. 6950, 69500U (2008); doi:10.1117/12.777919 included herein courtesy of M. Pfennigbauer and the SPIE Digital Library: www.SPIEDigitalLibrary.org

15.2   STLS Applications

Two types of TLS specification groups have been described to differentiate between TLS surveys have varying accuracy, control, and range requirements. "Type A" TLS surveys are hard surface topographic surveys with data collected at engineering level accuracy. "Type B" TLS surveys are topographic surveys with data collected at lower level accuracy. See *CSM* Chapter 11, "Engineering Surveys," for tolerances and accuracy standards for types of surveys: http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/11_Surveys.pdf

15.2-1   Type A - Hard surface topographic surveys:

• Pavement Analysis Scans (See Figures 15-3 and 15-4)

• Roadway/pavement topographic surveys

• Structures and bridge clearance surveys

• Engineering topographic surveys

• Detailed Archaeological Surveys

• Architectural and Historical Preservation Surveys

• Deformation and Monitoring Surveys

• As-built surveys

• Forensic surveys

15.2-2   Type B - Earthwork and lower-accuracy topographic surveys:

• Corridor study and planning surveys

• Asset inventory and management surveys

• Environmental Surveys

• Sight distance analysis surveys

• Earthwork Surveys such as stockpiles, borrow pits, and landslides

• Urban mapping and modeling

• Coastal zone erosion analysis

Note: The value of the STLS collected data is multiplied when it is "mined" for data for various uses and customers beyond its initial intended use.

15.3   STLS Project Selection

STLS equipment is available for State Highway System (SHS) project work. The following are factors to consider when planning use of STLS on a particular SHS project:

- Safety
- Project deliverables desired
- Project time constraints
- Site or structure complexity or detail required
- Length/size of project
- Traffic volumes and best available observation times
- Forecast weather and atmospheric conditions at planned observation time
- STLS system
    - Availability
    - Accuracy required
    - Technology best suited to the project and desired final products

15.4 STLS Equipment and Use

All of the equipment used to collect STLS data, to control the data, and to collect the quality control validation (check) points should be able to collect the data at the accuracy standards required for the project. This determination will be from the stated specifications for the equipment by the manufacturer. STLS accessories include tripods, targets, tribrachs, target poles, and a laptop computer. In some situations, additional power requirements may necessitate the use of portable generators. All survey equipment must be properly maintained and regularly checked for accuracy and proper function.

15.4-1 Eye Safety

Follow OSHA Regulation 1926.54 and manufacturers' recommendations when using any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. STLS equipment operators should never direct the laser toward personnel operating instruments with magnifying optics such as total stations or levels. Additionally, the eye safety of the traveling public and other people should be considered at all times and the equipment operated in a manner to ensure the eye safety of all.

15.4-2 Useful Range of Scanner

Since a laser scanner is capable of scanning features over long distances, and since the accuracy of the scan data diminishes beyond a certain distance, care should be taken to ensure that the final dataset does not include any portion of point cloud data whose accuracy is compromised by measurements outside the useful range of the scanner. The useful range will be determined by factors such as the range and accuracy specifications of the individual scanner as well as the accuracy requirements of the final survey products. Methods for accomplishing this might include the implementation of range and/or intensity filtering during data collection or culling any out-of-useful range data during post processing. Surface properties including color, albedo or surface reflectivity, and surface texture can limit scanner effective range.

15.4-3 Scanner Targets

Total station targets reduce pointing error when placed at long distances. Laser scanning targets, however, are designed for a specific distance. Most laser scanners do not have telescopes to orient the instrument to a backsight. Cylindrical, spherical, and planar targets must be scanned with a sufficient density to model their centers, with planar targets tending to yield better results. The size of the target, laser spot size, and distance from the scanner determine how precisely the center can be modeled. If the distance from the scanner to the target exceeds the manufacturer's recommended distance, the error can increase dramatically. Vendor-specific targets, which are tuned for the laser scanner frequency, are recommended. Follow the manufacturer's recommended distance for placement of targets. For example: Leica Twin-Target poles are designed to be used 50m from the scanner. They should be placed no more than 250 feet (75 meters) from the scanner.

15.5 STLS Specifications and Procedures

The radial survey method is used for all stationary STLS general order surveys. Individual general order scanned data points are not available for least-squares adjustment.

STLS collected survey data points are checked by various means including comparing the scan to the quality control validation points, reviewing the DTM, reviewing data terrain lines in profile, and redundant measurements. Redundant measurements with a LiDAR system can only be accomplished by multiple scans, either from the same set-up, or from a subsequent set-up that offers overlapping coverage. Table 15-1 lists the specifications required to achieve STLS general order accuracy.

15.5-1 Planning

Before the STLS project commences, the project area shall be reconnoitered to determine the best time to collect data to minimize excessive "artifacts" from traffic or other factors, and to identify obstructions that may cause data voids or shadows. Check weather forecast for fog, rain, snow, smoke, or blowing dust. Tall tripod set-ups may be used to help reduce artifacts and obstructions from traffic and pedestrians. Areas in the project that will be difficult to scan should be identified and a plan developed to minimize the effect on the final data, through additional set-ups or alternate methods of data collection. Safety should always be taken into consideration when selecting setup locations.

Site conditions should be considered to determine expected scanning distance limitations and required scan density to adequately model the subject area. Pavement analysis scans to identify issues such as surface irregularities and drainage problems require a scan point density of 0.10' or less, at a distance of 125' from the scanner (See Figure 15-3). Some scanners can maintain a constant desired point density throughout their effective range. Pavement analysis scans also require shorter maximum scanning distances and closer spacing of scanner control and validation points (See Figure 15-4) than other Scan Type A applications (See Figure 15-5).

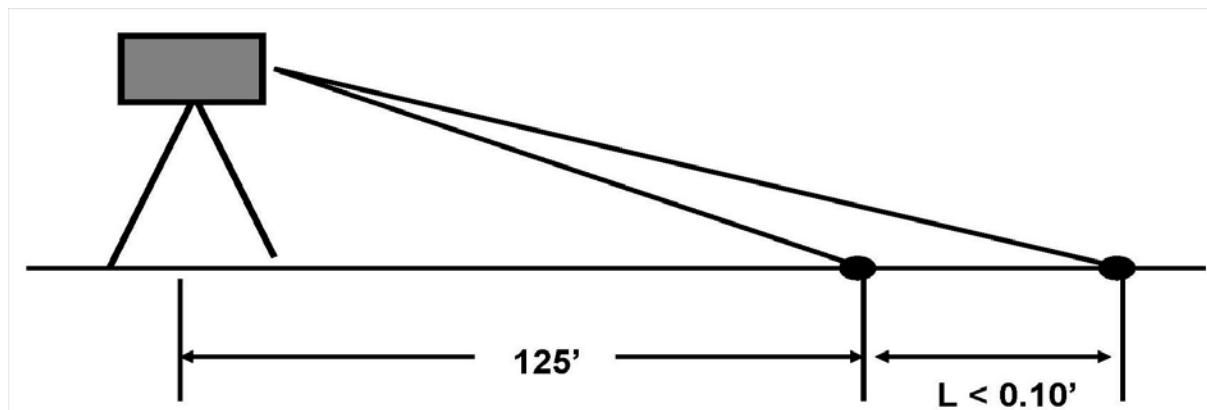**Figure 15-3 Scan Point Density for Pavement Analysis Scanning**

Image courtesy of the North Carolina Department of Transportation

15.5-2   Project Control Establishment and Target Placement

When performing Type A STLS surveys, the STLS control (scanner occupation and targeted control stations) points that will be used to control the point-cloud adjustment and validation points that will be used check the point-cloud adjustment of the STLS data shall be surveyed to third order or better horizontal and vertical accuracy standards as defined in the *CSM*. Best results are typically seen when the targeted control stations are evenly spaced horizontally throughout the scan. Variation in target elevations is also desirable. Targets should be placed at the recommended optimal distance from the scanner and scanned at high-density as recommended by the STLS manufacturer. Maximum scanner range and accuracy capabilities may limit effective scan coverage.

Pavement analysis scans to identify issues such as surface irregularities and drainage problems require shorter maximum scanning distances and closer spacing of scanner control and validation points than other Scan Type A applications (See Figures 15-3, 15-4 and 15-5).

Figure 15-4 Target Placement and Scan Coverage for Pavement Analysis Scanning
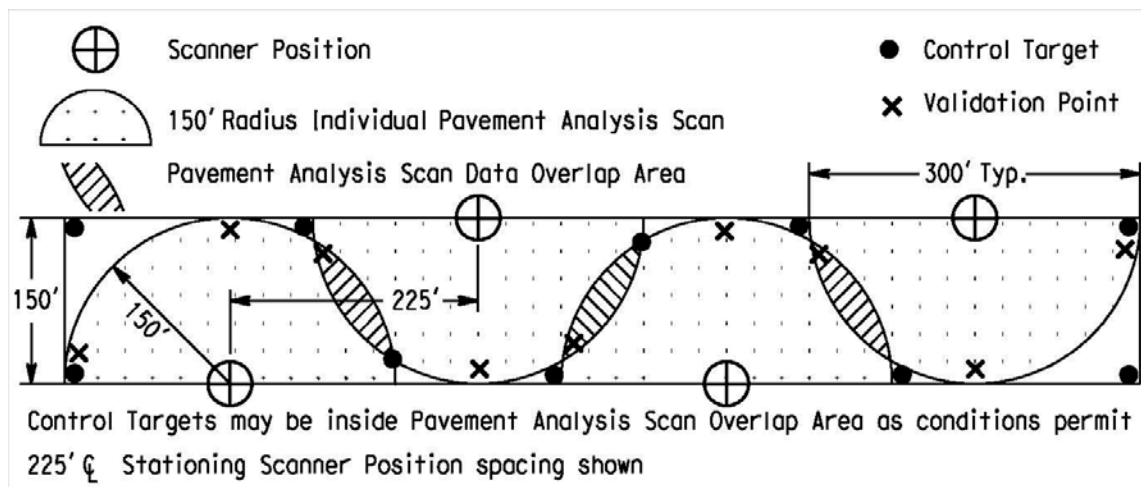
Target requirements vary. See Table 15-1, Note 2.

All Type A, hard surface topographic STLS surveys require control and validation point surveyed local positional accuracies of Hz ≤ 0.03' & Z ≤ 0.02'. Scan Type B, earthwork and other lower-accuracy topographic surveys require control and validation point surveyed local positional accuracies of Hz & Z ≤ 0.10' (See Table 15-1). All STLS control and validation points shall be on the project datum and epoch.

Figure 15-5 Target Placement and Scan Coverage - other Scan Type A applications
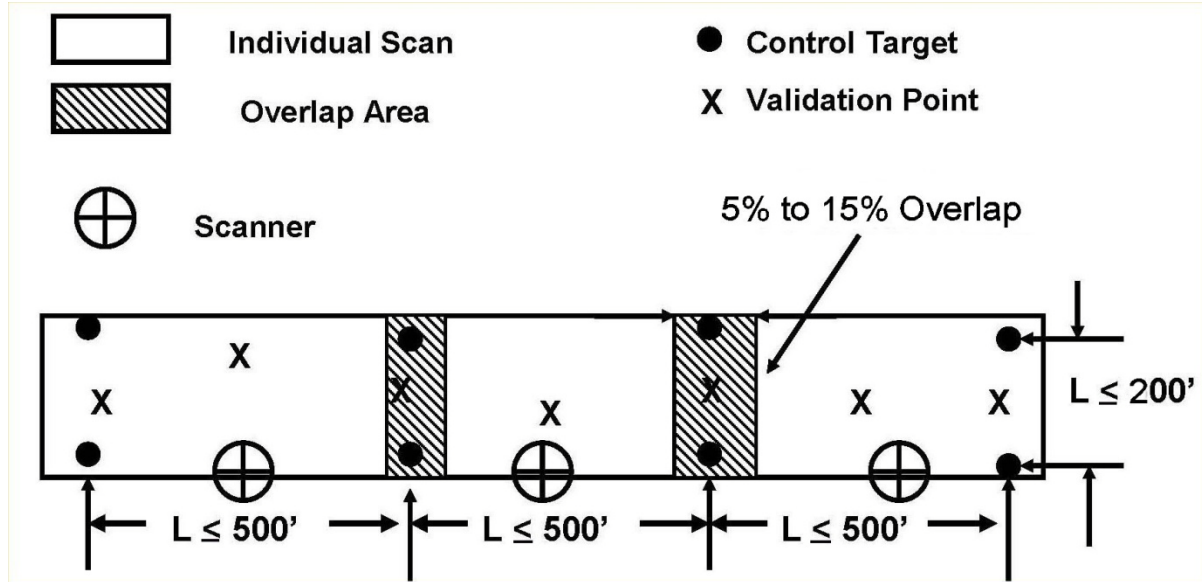

Image courtesy of the North Carolina Department of Transportation (modified by Caltrans). Fewer targets may be required. See Table 15-1, Note 2. Distances shown are maximums. Care must be taken not to exceed other limitations.

15.5-3   Equipment Set-up and Calibration

When occupying a known control point, ensure the instrument is over the point, measure and record the height of instrument (HI) and height of targets (HT) at the beginning of each set-up. It is advisable to check instrument height, plummet position, and target heights at the completion of each set-up. Scanners that do not have the ability to occupy points require additional targets incorporating good strength of figure to control each scan and establish scanner position by resection (See Table 15-1). Fixed height targets are required for Scan Type A applications, and recommended for Scan Type B applications. Ensure automatic STLS system calibration routines are functioning per the manufacturer's specifications.

15.5-4   Redundancy

STLS data collection shall be conducted in such a manner as to ensure redundancy of the data through overlapping scans. The data should be collected so that there is a 5% to 15% overlap (percentage of scan distance) from one scan to the next adjacent scan.

15.5-5   Monitoring STLS Operation

Monitoring STLS operation during the scan session is an important step in the scanning process. The system operator should note if and when the STLS system encountered difficulty and be prepared to take appropriate action to ensure data quality.

15.5-6   Quality Management Plan - QA/QC

Engineering survey data points collected using STLS are checked by various means including comparing scan points to validation points, reviewing the digital terrain model, reviewing data terrain lines in plan and profile, and redundant measurements. Redundant measurements with STLS can only be accomplished by scanner set-ups that offer overlapping coverage. Plan and profile views of overlapping registered point clouds should indicate precise alignment and data thickness of less than 0.03 ft at scan seams. Elevation comparison may be performed using profile, Digital Elevation Model (DEM) differences determined from point grid or Triangular Interpolation Network (TIN) data.

An STLS Quality Management Plan (QMP) shall include descriptions of the proposed quality control (QC) and quality assurance (QA) plan. The QMP shall address the requirements set forth in this document and any other project specific QA/QC measures (See the STLS checklist in Appendix 15B).

The QA/QC report shall list the results of the STLS including but not limited to the following documentation:

- Control survey reports
- STLS system statistical reports
- Scan seam comparison of elevation data from overlapping scans
- Statistical comparison of point cloud data and control points
- Statistical comparison of adjusted point cloud data and redundant validation points

Best practices include:

- Register data to established control network and check least square residuals to ensure standard deviation is within project requirements prior to leaving scan position
- Collect all data and imagery with traceability and redundant ties to the control network
- Prepare scan diagrams documenting scanner and target heights and depicting control geometry.

15.6   STLS Deliverables and Documentation

The desired deliverables from a scanning project should be identified in the planning stage. The ultimate value of the STLS collected data is multiplied when it is "mined" for data for various uses and customers beyond its initial intended use.

Documentation of surveys is an essential part of surveying work. The documentation of a scanning project must show a clear data lineage from the published primary control to the final deliverables.

15.6-1   STLS Deliverables

Different projects and customers require different types of deliverables, which can range from a standard CADD product to a physical three-dimensional (3D) scale model of the actual subject. Considerable office time is required to extract data from a point cloud to a CADD/DTM usable format. The ratio of field time to office time will vary greatly with the complexity of the scanned roadway and features. Resources for data extraction (computers, programs, and trained personnel) must be available.

Deliverables specific to STLS surveys may include, but are not limited to:

- XYZI or XYZIRGB files in ASCII, CSV, XML, LAS, ASTM E57 3D Imaging Data Exchange Format (E2761), or other specified format
- Registered point clouds
- Current Caltrans Roadway Design Software files
- Current Caltrans Drafting Software files
- Digital photo mosaic files
- 3D printing technology physical scale models of the subject
- Survey narrative report and QA/QC files
- Geospatial metadata files conforming to the current Caltrans standard:
  http://onramp.dot.ca.gov/gdmc/metadata_standards/MetadataStandards.pdf

15.6-2 STLS Documentation

The data path of the entire STLS project lineage must be defined, documented, assessable, and allow for identifying adjustment or modification. 3D data without a documented lineage is susceptible to imbedded mistakes, and is difficult to adjust or modify to reflect changes in control. An additional concern is that a poorly documented data lineage may not be legally supportable.

The survey narrative report, completed by the person in responsible charge of the survey (typically the Party Chief), shall contain the following general information, the specific information required by each survey method, and any appropriate supplemental information, including geospatial metadata files conforming to the current Caltrans standard.

- Project name & identification: County, Route, Postmile, E.A. or Project Identification, etc.
- Survey date, limits, and purpose
- Datum, epoch, and units
- Control found, held, and set for the survey
- Personnel, equipment, and surveying methods used
- Field notes including scan diagrams, control geometry, instrument and target heights, atmospheric conditions, etc.
- Problems encountered
- Any other pertinent information
- Dated signature and seal of the Party Chief or other person in responsible charge

Documentation specific to stationary STLS surveys includes, but is not limited to:

Control Lineage or Pedigree
- Primary and Project control held or established
- Traverse points
- Scanner occupied and targeted control points
- Validation points
- Adjustment report for control

Registration Reports
- Results of target and cloud to cloud registration
- QA/QC reports
- Results of finished products to validation points

Table 15-1 Stationary Terrestrial Laser Scanning Specifications

Operation/Specification	STLS Scan Application (See Section 15. 2)	
	Scan Type A	Scan Type B
Initial calibration of instrument at startup and during operation. Excessive vibration may render the scanner inoperable (See Note 1).	Each set-up	
Level compensator should be turned ON unless unusual situations (See Note 1) require that it be turned OFF.	Each set-up	
Minimum number of targeted control points required.	2 for each set-up (See Note 2)	
STLS control and validation point surveyed positional local accuracy.	H ≤ 0.03 foot V ≤ 0.02 foot	H and V ≤ 0.10 foot
Strength of figure: α is the angle between each pair of adjacent control targets measured from the scanner position.	Recommended $60º \leq \alpha \leq 120º$	Recommended $40º \leq \alpha \leq 140º$
Target placed at optimal distance to produce desired results	Each set-up	
Control targets scanned at high density (See Note 3)	Required	
Measure instrument height (when occupying control) and target heights	Yes	
Fixed height targets (when occupying control)	Required	Recommended
Check position of instrument and targets over occupied control points	Begin and end of each set-up	
Be aware of equipment limitations when used in rain, fog, snow, smoke or blowing dust, or on wet pavement.	Each set-up	
Distance to object scanned not to exceed best practices for laser scanner and conditions - Equipment dependant	Manufacturer's specification	
Distance to object scanned not to exceed scanner capabilities to achieve required accuracy and point density.	Each set-up	
Observation point density	Sufficient density to model object. (See Note 4)	
Overlapping adjacent scans (percentage of scan distance)	5% to 15%	
Maximum measurement distance to meet vertical accuracy standard for horizontal (pavement) surface measurements	260 feet (See Note 5)	N/A

Continued

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Table 15-1 Stationary Terrestrial Laser Scanning Specifications - Continued

| Operation/Specification	STLS Scan Application (See Section 15. 2)	
	Scan Type A	Scan Type B
Minimum measurement distance	Manufacturer's specification	
Registration of multiple scans in post-processing	Required	
Post-processing software registration error report	Required	
Registration errors not to exceed in any horizontal dimension	0.03 foot	0.15 foot
Registration errors not to exceed in vertical dimension	0.02 foot	0.10 foot
Independent control validation points (confidence measurements) to confirm registration	Minimum of three (3) per scan	Minimum of two (2) per scan

Notes:

1. Unusual situations could include bridge set-up with heavy truck traffic or high winds which cause excessive instrument vibration.

2. A *minimum* of two (2) targeted control points, are scanned at high density for stationary laser scanners set-up in a level orientation, using a dual-axis compensator, occupying, backsighting, and foresighting control points with known X, Y, and Z coordinate values. When using a scanner that does not meet these criteria, or the compensator is off, a *minimum* of three (3) targeted control points are required for each set-up. When known control is not occupied, backsighted, and foresighted, a *minimum* of four (4) targeted control points are required for each set-up.

3. Scan targets at high-density setting as recommended by the manufacturer or use manufacturer's auto target acquisition feature if available.

4. Pavement Analysis scan point density 0.10' at 125'.

5. Maximum pavement measurement distance for Pavement Analysis Scans is 150 feet.

6. Fixed height control targets are required for Type A and recommended for Type B STLS applications when targets occupy control points.

15.7 Mobile Terrestrial Laser Scanning

Mobile terrestrial laser scanning (MTLS) is an emerging technology that uses laser scanner technology in combination with Global Navigation Satellite Systems (GNSS) and other sensors to produce accurate and precise geospatial data from a moving vehicle. MTLS platforms may include Sport Utility Vehicles, Pick-up Trucks, Hi-Rail vehicles, boats, and other types of vehicles (See Figure 15-5). Safety and efficiency of data collection are compelling reasons to use mobile laser scanning. The potential to acquire a great deal of data in a short time is enormous, especially in areas that are not conducive to traditional methods of data collection. Data collection on 20 miles of highway per day is achievable by most systems. Imaging sensor capabilities may include hi-definition video or digital photography.

Figure 15-5 Typical MTLS Scanning Platforms
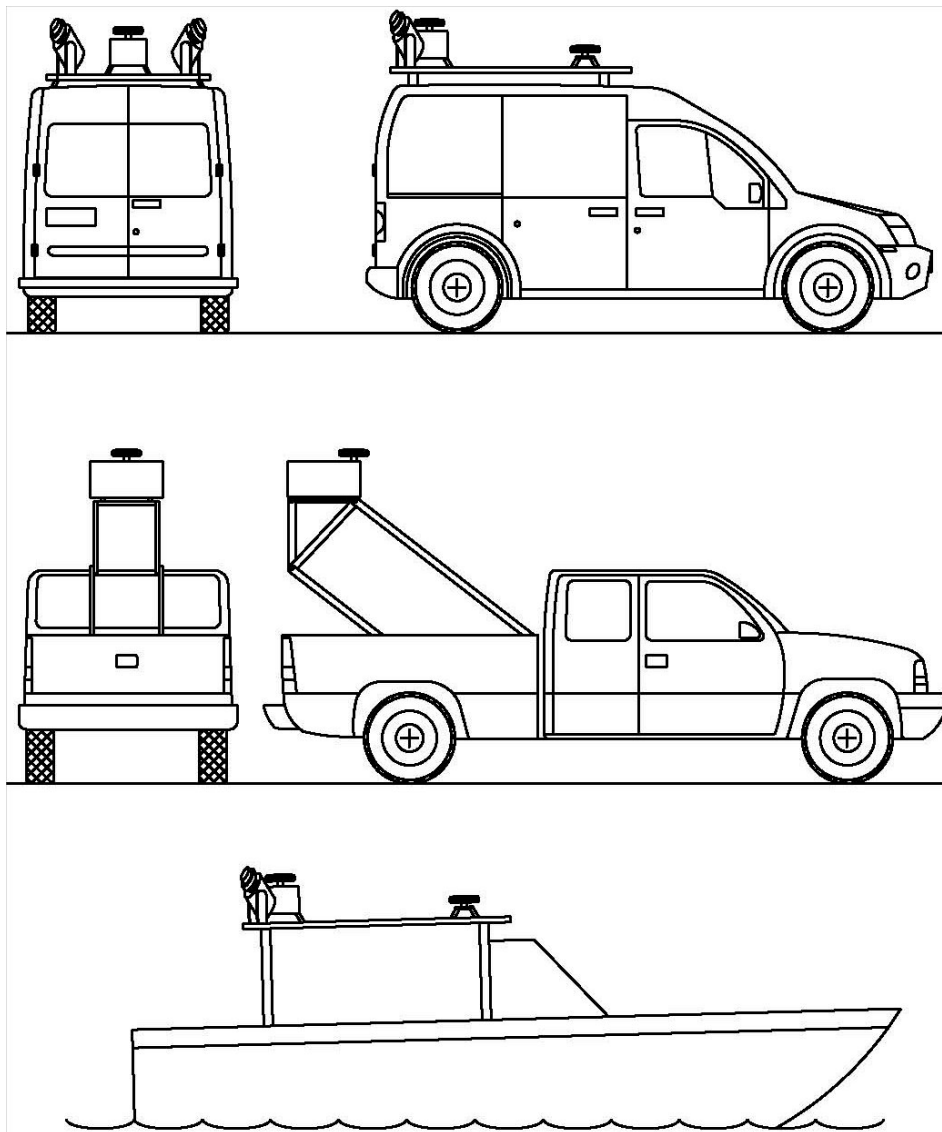
The MTLS collects laser measurement data continuously throughout each MTLS run. The position and orientation of the scanner(s) are determined using a combination of data from GNSS, an inertial measurement unit (IMU), and possibly other sensors, such as precise odometers. An IMU uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate and record the position, orientation, and velocity (direction and speed) of a moving object without the need for external references. IMUs are used on vehicles such as ships, aircraft, submarines, guided missiles, spacecraft, and MTLS systems. Within the MTLS the IMU is used to calculate change of XYZ position and orientation (roll, pitch and yaw) of the sensor array between GNSS observations, and during periods of reduced or no GNSS reception. By combining the laser range, scan angle, scanner position and orientation of the platform from GNSS and IMU data, highly accurate XYZ coordinates of the point scanned by each laser pulse can be calculated.

The laser pulse repetition rate in combination with the scanning mirror's deflection pattern determines the data collection rate. Surface point density is a function of the data collection rate and the vehicle speed. In the most advanced commercially available MTLS systems, the data measurement rate is typically 50,000 to 300,000 measurements per second per scanner, which allows the user to collect highly accurate data of a required ground point density within a very short period of time. The scanner(s) position is determined by post-processed kinematic GNSS procedures using data collected by GNSS antenna(s) mounted on the vehicle and GNSS base stations occupying project control (or continuously operating GNSS stations) throughout the project area. The GNSS solutions are combined with the IMU data to produce precise geospatial locations and orientations of the scanner(s) throughout the scanning process. The point cloud generated by the laser scanner(s) is registered to these scanner positions and orientations, and may be combined with digital imagery sensor data in proprietary software. The point cloud and imagery information provides a very detailed data set.

GNSS has vertical accuracy limitations and will not meet Caltrans Engineering Survey standards for pavement elevation surveys. Additional control points (local transformation points) within the MTLS scan area are required to calibrate the point cloud data by adjusting point cloud elevations. The point cloud is adjusted by a local transformation to well defined points throughout the project area to produce the final geospatial values. The final scan values are then compared to independently measured validation points.

Various vendors are currently deploying MTLS technology. The configuration of the scanner(s) and sensors varies greatly from vendor to vendor. Various mobile systems have different levels of positional accuracy due to error sources in the sensors and the GNSS environment.

15.8   MTLS Applications

See *CSM* Chapter 11, "Engineering Surveys," for tolerances and accuracy standards for specific types of surveys. http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/11_Surveys.pdf

15.8-1   Type A - Hard surface topographic surveys:

*   Engineering topographic surveys
*   As-built surveys
*   Structures and bridge clearance surveys
*   Deformation surveys
*   Forensic surveys

15.8-2   Type B - Earthwork and low-accuracy topographic surveys:

*   Corridor study and planning surveys
*   Asset inventory and management surveys
*   Environmental Surveys
*   Sight distance analysis surveys
*   Earthwork Surveys such as stockpiles, borrow pits, and landslides
*   Urban mapping and modeling
*   Coastal zone erosion analysis

Note: The value of the MTLS collected data is multiplied when it is "mined" for data for various uses and customers beyond its initial intended use.

15.9   MTLS Project Selection

The following are factors to consider when determining if MTLS is appropriate for a particular SHS project:

*   Safety
*   Project deliverables desired
*   Project time constraints
*   GNSS data collection environment
*   Length/size of project
*   MTLS system availability
*   Traffic volumes and available observation times

15.10   MTLS Equipment and Use

All of the equipment used to collect MTLS data, to control the data, and to collect the quality control validation points should be able to collect the data at the accuracy standards described below. This determination will be from the stated specifications for the equipment by the manufacturers.

15.10-1   Eye Safety

Follow OSHA Regulation 1926.54, ASTM standard E2641-09, and manufacturers' recommendations when using any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. Additionally, the eye safety of the traveling public and other people should be considered at all times and the equipment operated in a way to ensure the eye safety of all.

15.10-2   Useful Range of Scanner

Since a laser scanner is capable of scanning features over long distances, and the accuracy of the scan data diminishes beyond a certain distance, care should be taken to ensure that the final dataset does not include any portion of point cloud data whose accuracy is compromised by measurements outside the useful range of the scanner. The useful range will be determined by factors such as the range and accuracy specifications of the individual scanner as well as the accuracy requirements of the individual project. Methods for accomplishing this might include the implementation of range and/or intensity filtering during data collection or culling any out-of-useful range data during post-processing.

15.10-3   Local Transformation and Validation Points

Local transformation points serve as control for transformation of the point clouds. Validation points allow for QA/QC checks of the adjusted scan data. Local transformation and validation points may be targeted control points, recognizable features, or coordinate positions within the scans. When used, targets should be located as close to the MTLS vehicle path possible without compromising safety. The MTLS vehicle operator(s) should adjust the vehicle speed at the target area so that the target(s) will be scanned at sufficient density to ensure good target recognition. See Section 15.11-6 and Table 15-2 for spacing and accuracy requirements.

15.11 MTLS Specifications and Procedures

MTLS GNSS equipment must correspond with the requirements stated in Chapter 6, "GNSS Surveys" of the *CSM*. MTLS kinematic post-processing must comply with these specifications or applicable Caltrans Third-Order (Horizontal) GNSS Survey Specifications; whichever is more restrictive. MTLS kinematic GNSS/IMU data must be post-processed in forward and reverse directions (from beginning-to-end and end-to-beginning). Table 15-2 lists the specifications required to achieve general order MTLS accuracy.

15.11-1 Mission Planning

Before the MTLS project commences a mission planning session should be conducted to assure that there are enough satellites available during the data collection and that the PDOP meets the requirements. During the data collection there shall be a minimum of five (5) satellites in view for the GNSS Control Stations and the GNSS unit in the MTLS system. Additionally, the maximum PDOP value during acquisition shall be five (5). The project area shall be reconnoitered to determine the best time to collect the data to minimize excessive "artifacts" in the data collection from surrounding traffic or other factors, and to identify obstructions that may cause GNSS signal loss. Identify areas in the project that have poor satellite visibility and develop a plan to minimize the effect on the data, such as a densified network of transformation points and validation points.

15.11-2 GNSS Project Control

The GNSS Control Stations that will be used to control the post-processed kinematic adjustment of the MTLS data shall be placed at a maximum of 10-mile intervals to ensure that under normal circumstances, no processed baseline exceeds five (5) miles in length. Short baselines contribute to the best possible positional accuracy outcome. Dual redundant GNSS base stations are highly recommended to guard against the possibility of wasted effort and useless data from base station failure due to equipment, accident or human error in station setup. Dual base stations also allow redundant post-processing and 10-mile baseline post-processing in case of a base station failure. Locate one base station near the beginning of the project and another one near the end of the project. The horizontal accuracy standard of the GNSS Control Stations shall be second order or better and the vertical accuracy standard shall be third order or better as defined in the *CSM*.

15.11-3 Equipment Calibration

Before and after collecting the MTLS data all of the equipment in the MTLS system shall be calibrated to the manufacturer's specifications. Sensor alignment (bore sighting) procedures shall be performed prior to scanning if the system has been disassembled for transport.

Some MTLS systems may requires a safe location with relatively open sky to perform calibration routines before and/or after scanning passes. This may be as simple as parking for several minutes to collect static data for sensor alignment, bore sighting by performing multiple scans of a structure or building from different orientations, or it may require a larger area such as a parking lot to perform a series of figure "8" maneuvers.

15.11-4   Redundancy

MTLS data collection shall be conducted in such a manner as to ensure redundancy of the data. The data should be collected so that there is an overlap, which means that either more than one pass in the same direction on the SHS project, overlapping passes in opposite directions, or both shall be collected. Overlap dimensions: minimum of 20% sidelap.

15.11-5   Monitoring Equipment During Data Collection

Monitoring various component operations during the scan session is an important step in the QA/QC process. The system operator should be aware and note when the system encountered the most difficulty and be prepared to take appropriate action in adverse circumstances.

The MTLS equipment shall be monitored throughout the data collection to track the following as well as any other factors that need monitoring:

•   Degraded or lost GNSS reception.

•   Distance traveled during, or time duration of degraded or lost GNSS reception (resulting in uncorrected IMU drift).

•   Proper functioning of the laser scanner.

•   Vehicle Speed appropriate for desired point density.

## 15.11-6   Local Transformation and Validation Requirements

In order to increase the accuracy of the collected and adjusted geospatial data, a local transformation of the point clouds shall be conducted. Different types of local transformations may be employed. The most common is a simple elevation adjustment of the vertical values between established local transformation points and the corresponding values from the point clouds. Local transformation points shall be located at the beginning, end, and evenly spaced throughout the project to ensure that the project is "bracketed."

Validation points are used to check the geospatial data adjustment to the local transformation points. Validation Points shall be located at the beginning, end, and evenly spaced throughout the project (See Figure 15-6).

For Type A MTLS surveys, bracket the scanned area on both sides of the roadway with local transformation points at a maximum of 1500-foot roadway centerline stationing intervals. Validation points should be on both sides of the scanned roadway, at centerline stationing intervals not exceeding 500 feet. Type A MTLS surveys require local transformation points and validation points to have surveyed local positional accuracies of Hz ≤ 0.03 foot & Z ≤ 0.02 foot or better. The preferred method of establishing Type A MTLS local transformation point elevations is differential leveling to Caltrans Third Order or better specifications.

For Type B MTLS surveys, bracket the scanned area on both sides of the roadway with local transformation points at a maximum of 2400-foot roadway centerline stationing intervals. Validation points should be on both sides of the scanned roadway, at centerline stationing intervals not exceeding 800 feet. Type B MTLS surveys require local transformation and validation points to have surveyed local positional accuracies of Hz & Z ≤ 0.10 foot or better (See Table 15-2).

Figure 15-6 Typical MTLS Type A Local Transformation and Validation Point Layout
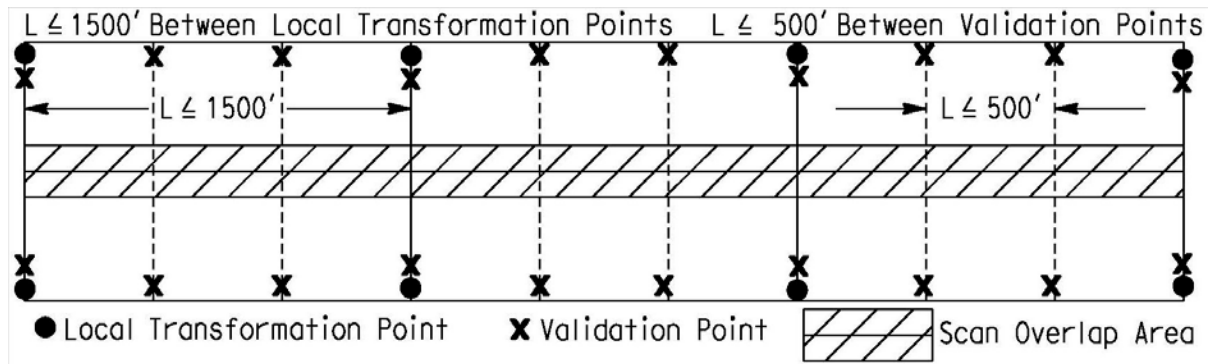
15.11-7   Quality Management Plan - QA/QC

Engineering survey data points collected using MTLS are checked by various means including comparing scan points to validation points, reviewing the digital terrain model, reviewing data terrain lines in profile, and comparing redundant measurements. Redundant measurements with MTLS can only be accomplished by multiple scan runs or passes that offer overlapping coverage.

The MTLS data provider shall provide a QMP that includes descriptions of the proposed quality control and quality assurance plan. The QMP shall address the requirements set forth in this document as well as other project specific QA/QC measures (See the MTLS checklist in Appendix 15C).

The QA/QC report shall list the results of the MTLS including but not limited to the following documentation:

- MTLS system reports
- PDOP values during the survey
- Separation of forward and reverse solutions (difference between forward and reverse post-processed roll, pitch, yaw and XYZ positions solution). Forward and reverse refers to time: processing from beginning-to-end and end-to-beginning.
- Areas of the project that the data collected exceeded the maximum elapsed time or distance traveled of uncorrected IMU drift due to degraded, lost, or obstructed GNSS signal reception.
- Comparison of elevation data from overlapping (sidelap) runs
- Comparison of points at the area of overlap (endlap) if more than one GNSS base is used.
- Statistical comparison of point cloud data and finished products to validation points
- Statistical comparison of adjusted point cloud data and redundant validation points

15.11-8   National Standard for Spatial Data Accuracy (NSSDA)

Final MTLS geospatial data accuracy reporting shall conform to the NSSDA requirements:
http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

15.12   MTLS Deliverables and Documentation

Different projects and customers require different types of deliverables. One of the inherent features and fundamental advantages of laser scan data is that it is acquired, processed and delivered in digital format allowing the user to generate laser scan-derived end products for a very wide range of applications and customers beyond the original intent.

Documentation of surveys is an essential part of surveying work. The documentation of a scanning project must show a clear data lineage from the published primary control to the final deliverables.

15.12-1   MTLS Deliverables

The deliverables from a MTLS project should be specified in the contract, task order, or work request with the provider. If a point cloud is the final deliverable, considerable office time will be required to extract data in a CADD/DTM usable format. The ratio of field time to office time will vary greatly with the complexity of the scanned roadway. Resources for data extraction (computers, programs, and trained personnel) must be available. If the mobile scan provider is delivering a finished CADD/DTM file, Caltrans office time will be reduced to QA of the final product.

The simplest form of the processed MTLS data is a "point cloud", which can be saved in a scanner specific format or an ASCII file format containing XYZI data. If image overlay data is available, the post-processed point cloud may be delivered in an XYZIRGB format.

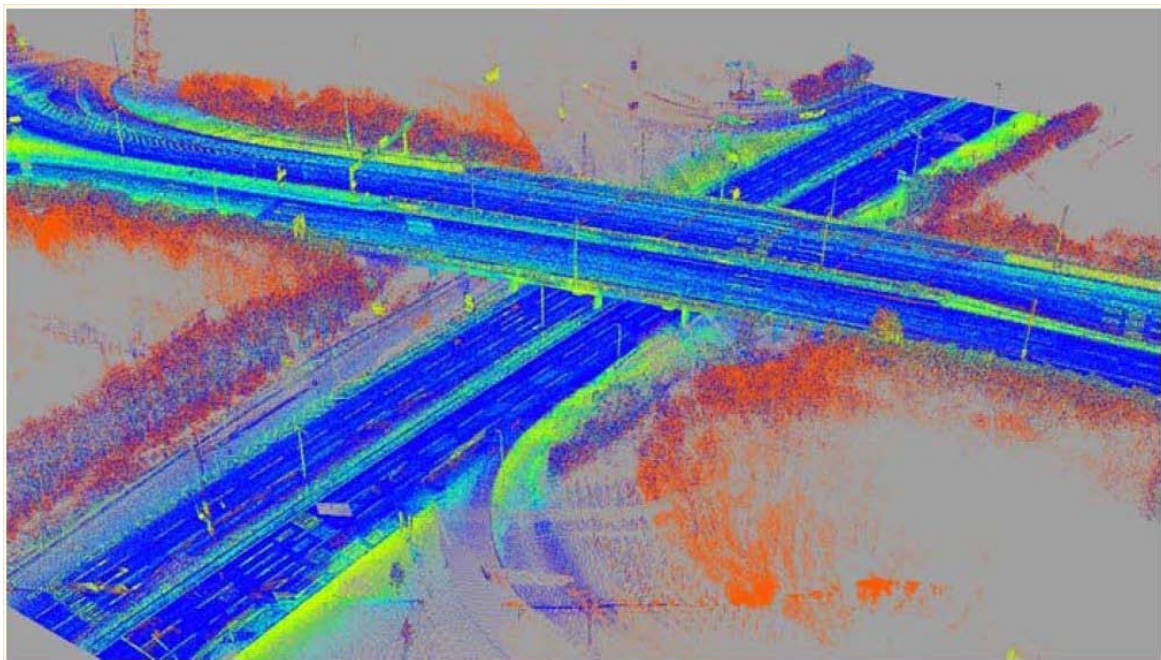**Figure 15-7 MTLS Point cloud data**

Figure 15-8 MTLS Point cloud data from Figure 15-7 converted to a CADD model

Figures 15-7 and 15-8 originally published in "Lynx Mobile Mapper^{TM}: The New Survey Technology" Zampa, F. and Conforti, D. in the Proceedings of the American Society for Photogrammetry and Remote Sensing (ASPRS), (2009); ISBN 1-57083-090-8 included herein courtesy of ASPRS. http://www.asprs.org/publications/proceedings/baltimore09/0106.pdf

Point cloud data can be imported into various software packages. Further data manipulation, infusing other types of data and the use of analytical tools with the imported point cloud create a variety of value-added products.

In addition, a geospatial metadata file specifying the units and datum of the XYZ coordinates in ASCII point cloud files should be provided. The georeferenced image files (in common image format such as jpg, tiff, png, etc) should also be deliverable if they are available.

Deliverables specific to MTLS surveys may include, but are not limited to:

• Registered point clouds (XYZI or XYZIRGB files) in ASCII, CSV, ASTM E57 3D Imaging Data Exchange Format (E2761), XML, LAS, or other specified format

• Raw data files

• Current Caltrans Roadway Design and Drafting Software files

• Digital video or photo mosaic files

• Survey narrative report and QA/QC files

• Geospatial metadata files conforming to the current Caltrans standard:
  http://onramp.dot.ca.gov/gdmc/metadata_standards/MetadataStandards.pdf

15.12-2   MTLS Documentation

The documentation of MTLS projects must show clear data lineage from the published primary control to the final deliverables. The data path of the entire process must be defined, documented, assessable, and allow for identifying adjustment or modification. 3D data without a documented lineage is susceptible to imbedded mistakes, and difficult to adjust or modify to reflect changes in control. An additional concern is that a poorly documented data lineage would not be legally supportable.

The survey narrative report, completed by the person in responsible charge of the survey (typically the Party Chief), shall contain the following general information, the specific information required by each survey method, and any appropriate supplemental information, including geospatial metadata files conforming to the current Caltrans standard.

- Project name & identification: County, Route, Postmile, E.A. or Project Identification, etc.
- Survey date, limits, and purpose
- Datum, epoch, and units
- Control found, held, and set for the survey
- Personnel, equipment, and surveying methods used
- Problems encountered
- Any other pertinent information such as GNSS observation logs
- Dated signature and seal of the Party Chief or other person in responsible charge

Documentation specific to mobile terrestrial laser scanning surveys includes, but is not limited to:

Control Lineage or Pedigree

- Primary control held or established
- Project control held or established
- Local transformation points
- Validation points
- Adjustment report for control and validation points
- Base station observation logs (occupation data, obstruction diagram, atmospheric conditions, etc.)

Control for Scanner Registration and QC

- Local transformation points
- Validation points
- GNSS Accuracy Report
- GNSS satellite visibility and PDOP reports
- IMU Accuracy Report
- Trajectory reports

Registration Reports

- Results of target and cloud to cloud registration

- QA/QC reports as described in Section 15.11-7

- Results of finished products to validation points

- Geospatial metadata files conforming to the current Caltrans standard:

    http://onramp.dot.ca.gov/gdmc/metadata_standards/MetadataStandards.pdf

Table 15-2 Mobile Terrestrial Laser Scanning Specifications

Operation/Specification	MTLS Scan Application (See Section 15.8)	
	Scan Type A	Scan Type B
MTLS equipment must be capable of collecting data at the intended accuracy and precision for the project.	Required	
Initial calibration of MTLS system (per manufacturers specs)	As Required	
Dual-frequency GNSS recording data at 1 Hz or faster	Required	
Minimum IMU positioning data sampling rate capability	100 Hz	
Maximum IMU Gyro Rate Bias	1 degree per hour	
Maximum IMU Angular Random Walk (ARW)	0.125 degree per √hour	
Maximum IMU Gyro Rate Scale Factor	150 ppm	
Minimum IMU uncorrected positioning capability due to lost or degraded GNSS signal	GNSS outage of 60 seconds or 0.6 miles distance travelled	
Maximum duration or distance travelled with degraded or lost GNSS signal resulting in uncorrected IMU positioning	GNSS outage of 60 seconds or 0.6 miles distance travelled	
Maximum uncorrected IMU X-Y positioning drift error for 60 second duration or 0.6 mile distance of GNSS outage	0.33 foot (0.100m)	
Maximum uncorrected IMU Z positioning drift error for 60 second duration or 0.6 mile distance of GNSS outage	0.23 foot (0.070m)	
Maximum uncorrected IMU roll and pitch error/variation for 60 second duration or 0.6 mile distance of GNSS outage	0.020_degrees RMS	
Maximum uncorrected IMU true heading error/variation for 60 second duration or 0.6 mile distance of GNSS outage	0.020 degrees RMS	
Project control should be the constraint for GNSS positioning	Yes	
Minimum order of accuracy for GNSS base station horizontal (H) and vertical (V) project control	Horizontal – 2nd Vertical – 3rd	
MTLS Local Transformation Point and Validation Point surveyed positional accuracy requirements.	H ≤ 0.03 foot V ≤ 0.02 foot	H and V ≤ 0.10 foot
GNSS base stations located at each end of project	Recommended	
Maximum post-processed baseline length	Five (5) miles	
Maximum PDOP during MTLS data acquisition	Five (5)	

Continued

Table 15-2 Mobile Terrestrial Laser Scanning Specifications - Continued

Operation/Specification	MTLS Scan Application (See Section 15.8)	
	Scan Type A	Scan Type B
Minimum number of common healthy satellites in view for GNSS base stations and mobile scanner (See Notes 1 and 4)	Five (5)	
Minimum overlapping coverage between adjacent runs	20% sidelap	
Monitor MTLS system operation for GNSS reception	Throughout each pass	
Monitor MTLS system operation for IMU operation and distance and duration of any uncorrected drift	Throughout each pass	
Monitor MTLS laser scanner operation for proper function	Throughout each pass	
Monitor MTLS system vehicle speed	Throughout each pass	
Minimum orbit ephemeris for kinematic post-processing	Broadcast	
Observations – sufficient point density to model objects (See Note 1)	Each pass	
Vehicle speed – limit to maintain required point density	Each pass	
Filter data to exclude measurements exceeding scanner range	Each pass	
Local transformation point maximum stationing spacing throughout the project on each side of scanned roadway	1500 foot intervals	2400 foot intervals
Validation point maximum stationing spacing throughout the project on each side of scanned roadway for QC purposes as safety conditions permit. (See Note 3)	500 foot intervals	800 foot intervals

Notes:

1. Areas in the project that have poor satellite visibility should be identified and a plan to minimize the effect on the data developed.
2. The project area shall be reconnoitered to determine the best time to collect the data to minimize excessive "artifacts" in the data collection from surrounding traffic or other factors.
3. If safety conditions permit, additional validation points should be added in challenging GNSS environments such as mid sections of tunnels and urban canyons.
4. GNSS coverage of less than five (5) satellites in view must not exceed the uncorrected position time or distance travelled capabilities of the MTLS system IMU.

Appendix 15A: Glossary

SEE ALSO: ASTM E57 DEFINITIONS ASTM E2544 (3D Imaging Standards)

http://www.astm.org/Standards/E2544.htm

Albedo – The fraction of light energy reflected by a surface, usually expressed as a percentage; also called the reflection coefficient.

Artifacts – Erroneous data points that do not correctly depict the scanned area. Objects moving through the scanner's field of view, temporary obstructions, highly reflective surfaces, and erroneous measurements at edges of objects (also known as "Edge Effects") can cause artifacts. Erroneous depiction of features can be due to inadequate or uneven scan point density.

Data Voids – Gaps in scan data caused by temporary obstructions or inadequate scanner occupation positions. Overlapping scans and awareness of factors causing data shadows can help mitigate data voids. Some data voids are caused by temporary obstructions such as pedestrians and vehicles.

Decimation – Reduction of the density of the point cloud.

Inertial Measurement Unit (IMU) – A device that senses and quantifies motion by measuring the forces of acceleration and changes in attitude in the pitch, roll, and yaw axes using accelerometers and gyroscopes.

Intensity – A value indicating the amount of laser light energy reflected back to the scanner.

Noise – Erroneous measurement data resulting from random errors.

Phantom Points – See "Artifacts" above.

Phase based measurement – Distance measurements based on the difference in a light's sinusoidally modulated power and it's reflected return from a surface.

Point Cloud – The 3D point data collected by a laser scanner from a single observation session. A point cloud may be merged other point clouds to form a larger composite point cloud. Data from within a point cloud may be used to produce traditional survey products, and point clouds may be specified as a deliverable.

Point Density – The average distance between XYZ coordinates in a point cloud, typically at a specified distance from the scanner. The *point density* specified by the client or selected by the contractor should be understood as the maximum value for the subject in question and should be dense enough to achieve extraction of detail at the scales specified for the project.

Registration – The process of joining point clouds together or transforming them onto a common coordinate system. Registration can be by use of a) known coordinates and orientations b) target transformation or c) surface matching algorithms.

Resolution – The ability to detect small objects or object features in the point cloud. See: Investigating Laser Scanner Accuracy, W. Boehler, M. Bordas Vicent, A. Marbs, i3mainz, Institute for Spatial Information and Surveying Technology, April 2004. http://scanning.fh-mainz.de/scannertest/results200404.pdf

Scan – The acquiring of point cloud data by a Lidar system.

> **Detail Scan** – A higher point density scan.

> **Overview Scan** – A scan to gather general details of an area.

Scan Density – See "Point Density" above.

Scan Speed – The rate at which individual points are measured and recorded.

Time-of-flight measurement – Distance measurements based on the time between emitting a pulse of light and the detecting the reflection of the pulse.

Trajectory report – MTLS system and positional performance data from each scanning pass produced by post-processing software. Reported parameters may include satellites in view, PDOP, GDOP, uncorrected IMU distance, uncorrected IMU duration, difference in positional solutions between forward and backward processing, and estimated positional accuracy.

Wave-form processing – Also called "echo digitization." Scanner system that uses the pulsed time-of-flight technology and internal real-time processing capabilities of multiple returns to identify multiple targets.

XYZI – Scaner file format showing X & Y coordinate, Z elevation and reflection Intensity values.

XYZIRGB– Scaner file format showing X & Y coordinate, Z elevation, reflection Intensity, and Red, Green, Blue color values.

Appendix 15B: STLS Checklist

A. Materials needed BEFORE scanning:

1) Who is the Project Manager?
2) Purpose of project mapping
3) Map units
4) Project coordinate system
5) Scanner calibration data
6) Proposed scanner control plan
7) Proposed scanner occupation plan
8) Proposed safety plan
9) Proposed validation points
10) Proposed schedule for delivery of Items B and C to the client

B. Materials needed AFTER scanning and BEFORE registration and data mining:

1) Scanner registration control accuracy reports should contain the following:
   Scanner occupation points
   Targeted control points
   Ground validation points
   Statistical comparison of point cloud data and control points
   Statistical comparison of adjusted point cloud data and redundant validation points

2) The Control Report should contain the following:
   Table showing the difference in elevation (dZ) between control points and STLS measured points
   Average, Minimum and Maximum dZ
   Average magnitude, RMS and standard deviation

C. Materials needed AFTER registration and data mining has been completed:

1) Classified point cloud (LAS, ASCII, or other specified format files)
2) Georeferenced digital photographs
3) CADD files
4) 3D printing technology physical scale models of the subject if required
5) Survey narrative report and QA/QC files

Appendix 15C: MTLS Checklist

A. Materials needed BEFORE the mission:

1) Who is the Project Manager?
2) Purpose of project mapping
3) Map units
4) Project coordinate system
5) Scanner calibration data
6) Proposed driving plan
7) Proposed safety plan
8) GNSS satellite visibility and PDOP forecasts
9) Suitable driving speed to obtain required point density
10) Proposed base station locations
11) Proposed local transformation point locations
12) Proposed schedule for delivery of Items B and C to the client

B. Materials needed AFTER the mission and BEFORE vectoring:

1) The GNSS Accuracy Report should contain the following:
    Forward/Reverse or Combined Separation plot
    Number of Satellites Bar plot
    PDOP, HDOP, VDOP plots
    L1 Satellite Lock/Elevation plot
    Estimated Position Accuracy plot

2) The IMU Accuracy Report should contain the following:
    IMU Position RMS plot
    GNSS/IMU Position Differences plot

3) The Control Report should contain the following:
    Table showing the dZ between validation points and MTLS measured points
    Average, Minimum and Maximum dZ
    Average magnitude, RMS and standard deviation

C. Materials needed AFTER vectoring has been completed:

1) Classified point cloud (LAS, ASCII, or other specified format files)
2) Georeferenced digital photographs/videos
3) CADD files
4) Survey narrative report and QA/QC files